Interferometry, spectroscopy and lensless imaging with extreme ultraviolet radiation

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Extreme ultraviolet radiation

Outline of this talk:

• Extreme ultraviolet radiation and its applications
• High harmonic generation, lasers and EUV spectroscopy
• EUV interferometry and Fourier transform spectroscopy
• Lensless imaging with EUV radiation
• Conclusions
Typical size of lithographic structures

(nano)transistors by Intel

130 nm
2003

90 nm
2005

65 nm
2007

45 nm
2009 – 2011

32 nm
2014

22 nm
later

??
??
The inside of a chip

So how do you image this?
Interesting properties of EUV radiation

1) Short wavelength $\rightarrow$ diffraction from nanoscale objects

2) Element-selectivity $\rightarrow$ many elements have spectral transmission windows

3) High photon energy $\rightarrow$ provides access to core levels

H. Stiel et al., MBI Berlin

S. Mathias et al. PNAS 109, 4792 (2012)
Table-top EUV sources

**Plasma sources**
(pumped by laser or electric discharge)

- Incoherent, $4\pi$ emission
- Nanosecond pulses (typical)
- Several % conversion efficiency
- Multiple Watts average power
- Debris from plasma

**High-harmonic generation**

- Coherent, diffraction-limited beams
- Attosecond pulse trains
- Conversion efficiency $10^{-5} – 10^{-9}$
- $\mu$W average power
- Need to separate EUV from IR
High harmonic generation

Intense laser modifies Coulomb potential → electron tunnels and accelerates in laser field

Field changes sign → electron returns to the parent ion

Recollision, electron energy converted into XUV photon

IR and EUV waves need to remain in phase for coherent buildup:

\[ \Delta k \approx \frac{q u_{11}^2 \lambda_L}{4 \pi a^2} - q p(1 - \eta) \frac{2 \pi}{\lambda_L} (\Delta \delta + n_2) + q p \eta N_a r_e \lambda_L \]

geometric atoms free electrons

Need to avoid excessive ionization, limits flux scaling by intensity
Typical HHG spectra

HHG in Argon, \( \lambda_{\text{laser}} = 800 \text{ nm}, E = 1 \text{ mJ}, 30 \text{ fs} \)
- Series of discrete odd ‘harmonics’
- Interference of a train of attosecond EUV bursts, produced every half-cycle

HHG in Helium, \( \lambda_{\text{laser}} = 1300 \text{ nm}, E = 1 \text{ mJ}, 40 \text{ fs} \)
- Harmonics blend into a continuum
- Only few (or one) attosecond bursts
Coherent EUV source development

- Intense few-cycle laser pulses are needed for HHG.
- Produced by optical parametric chirped pulse amplification (OPCPA).


XUV spectroscopy

**Classical grating-based spectrometer**: use diffraction to disperse different wavelengths over a spatial axis.

**Fourier-transform spectroscopy**: measure temporal coherence function and retrieve frequency information by Fourier transform.

*Sub-λ stability essential!*
Ultra-stable tunable interferometer

- Birefringent wedges from α-BBO
- Common path geometry ensures stability.

- Wedge angles and birefringence control optical path length step size.
- 10 micrometer wedge displacement $\rightarrow$ 0.92 fs delay change
- Piezo-stage with 5 nanometer precision $\rightarrow$ 0.46 attosecond delay steps possible

EUV interferometry

• HHG setup combined with ultra-stable common-path interferometer:
  
  ![Diagram of EUV interferometry setup](image)

  - Lens
  - Pulsed Valve
  - Al Filter
  - XUV Camera

• HHG in Argon with >1 mJ ~20 fs pulses

• Individual pulses should not influence each other during the HHG process → spatially separated HHG zones.

• Collinear beams, overlap after finite distance due to beam divergence.
Fourier transformation of the time delay scan on a single pixel yields the spectrum at the location of that pixel.

Linear autocorrelation of two HHG beams yields coherence length.
HHG Fourier transform spectroscopy

- HHG in Neon yields broader spectra and shorter coherence times.
- HHG detected down to 17 nm wavelength (Al filter cutoff).
- Stability of interferometer and HHG phase coherence maintained at sub-nm level.

HHG-FTS in Neon:

![Graphs showing HHG-FTS in Neon](image)

G.S.M. Jansen et al., Optica 3, 1122 (2016)
Spatial interference and interferometer stability

Spatial Fourier transform yields a single-shot HHG spectrum:

Phase detection of a single harmonic vs time delay yields timing stability:

Measured RMS timing stability of 0.8 as, or 0.25 nm optical path length
Spatially resolved XUV spectroscopy

Titanium layer on 250x250 µm silicon nitride foil with a 50 µm hole in it:

Measurement of the transmitted spectrum of Neon HHG on each CCD pixel

G.S.M. Jansen et al., Optica 3, 1122 (2016)
Lensless coherent diffractive imaging

Numerical reconstruction of an object from a coherent diffraction pattern, instead of the use of optical components for image formation:

Measured diffraction yields intensity, phase also needed for image reconstruction

> The challenge is to retrieve the missing phase information.

- Resolution = $\lambda / 2 \sin \theta$
- High spatial and temporal coherence important.
Image reconstruction from a diffraction pattern

Object:

Support

Needs additional information:
- Finite object support
- Positivity
- Atomicity
- ...

Other approaches use multiple measurements instead of an object constraint (ptychography, multi-wavelength/multi-distance phase retrieval, etc.)

Coherent diffractive imaging: examples

- Several successful experiments have been performed using CDI.
- Resolutions of 20-25 nm achieved.

Freeze-dried yeast cell at 30 nm resolution
Synchrotron, 750 eV photons:

Magnetic nanostructures, 50 nm resolution
Synchrotron, 778 eV photons:

D. Shapiro et al., PNAS 102, 15343 (2005)

Bandwidth limitations in lensless imaging

• Lensless imaging requires a coherent, monochromatic source, since the diffraction angle is directly proportional to wavelength.
• Broadband sources lead to blurred diffraction patterns:

  Monochromatic:                     Broadband:

• Limits the resolution, in extreme cases prevents image reconstruction.
• Spectral filtering is possible, but at the cost of serious flux reduction.
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Two-pulse Fourier-transform imaging

- Combination of imaging and Fourier transform spectroscopy
- On each CCD pixel, a Fourier-transform spectrum is recorded of the light diffracted onto that specific pixel.

- Allows reconstruction of ‘monochromatic’ diffraction patterns for all spectral components in the pulse.
- The full spectrum is used throughout the entire measurement.
Lensless imaging with XUV radiation

- Sample is a Nickel grid on a 300 nm thick Aluminium foil.
- The Al-foil is partially transparent below 70 nm wavelength.
- Spectrally resolved images at 62, 53 and 47 nm wavelength.
- Scan parameters: 512 steps of 6.6 nm (22 attoseconds).

Broadband diffraction:

HHG spectrum:

Diffraction at 17\textsuperscript{th} harmonic:
Multi-wavelength iterative phase retrieval

- For Fresnel diffraction, measurements at multiple propagation conditions enable unique image reconstruction.
- The Fresnel diffraction integral describes the field propagation:

\[
E(x, y, z) = \frac{e^{ikz}}{i\lambda z} \iint E(x', y', 0) e^{i\frac{\pi}{\lambda z}[(x-x')^2+(y-y')^2]} 
\]

Lensless imaging at short wavelengths

- We use diffraction patterns at 62 nm, 53 nm and 47 nm as input for our multi-wavelength phase retrieval algorithm.
- Resolution limited by NA to 6.8 μm, can easily be improved in future experiments.

Nickel grid behind 200 nm thick Aluminium layer

XUV Fourier-transform holography

- Fourier-transform holography provides a direct phase measurement.
- Pinhole-generated reference wave acts as a delta function.
- Signal intensity: \[ I = \left| E_{\text{ref}} \right|^2 + \left| E_{\text{obj}} \right|^2 + E_{\text{ref}} E_{\text{obj}}^* + E_{\text{ref}}^* E_{\text{obj}} \]

\[ \xrightarrow{\text{Resolution limited by aperture diameter}} \]
\[ \xrightarrow{\text{Signal proportional to aperture area (~d}^2) } \]
XUV holography

Broadband hologram:

Hologram at $\lambda=33$ nm:

Fourier transform:

- Signal from smallest pinhole below noise level
- Flux limited by HHG beam size
- Next step: focus the XUV beam
HHG wavefront measurements

Alternatively, known structures can be used to diagnose the XUV beam itself.

Hartmann mask:

2D wavefront reconstruction, can be combined with two-pulse scan for spectral resolution.
HHG wavefront measurements

Lateral shearing interferometry: interference of two displaced copies of a HHG beam.

Provides a spatial derivative of the phase:

$$
\psi(x) = \varphi(x + \Omega) - \varphi(x)
$$

With a known ‘shear’ $\Omega$, integration yields the spatial phase $\varphi(x)$

Single-shot spectrally resolved measurement (but 1D information)
Conclusions

High harmonic generation is a versatile tool for extreme ultraviolet experiments with a table-top setup, such as:

- Interferometry with HHG beams at 17 nm wavelength and beyond.

- Fourier transform spectroscopy with HHG, enabling spatially resolved XUV spectroscopy.

- Spectrally resolved lensless XUV imaging, using the full spectrum and flux of a HHG source.
EUV Generation and Imaging @ ARCNL

**Group leaders**
- Stefan Witte
- Kjeld Eikema
- Aneta Stodolna
- Denis Rudolf
- Nik Noest

**PhD students**
- Tiago Pinto
- Lars Freisem
- Mengqi Du
- Alessandro Antonceccchi
- Randy Meijer
- Dirk Boonzajer Flaes
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**Postdocs**
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**Technician**
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- Randy Meijer
- Dirk Boonzajer Flaes
- Matthijs Jansen

**Logos**
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### Jobs and internships

- **Group leader / assistant professor: High-harmonic generation and EUV physics**
  - October 25, 2016 · [Group leaders](http://www.arcnl.nl)

  The Advanced Research Center for Nanolithography (ARCNL) is looking for a tenure-track group leader in the field of EUV physics and high-harmonic generation. The successful candidate will develop a world-class ...

- **Lensless microscopy and 3D imaging with visible and EUV sources**
  - September 26, 2016 · [Postdoc positions](http://www.arcnl.nl)

  The postdoc will develop new methods for high-resolution lensless microscopy using visible, near-infrared and extreme ultraviolet radiation. You will work on high-speed imaging applications, visualization of (sub-)surface features in metals ...

- **Master student projects in Nanophotochemistry ARCNL**
  - April 13, 2016 · [Scientific internships](http://www.arcnl.nl)

  The overall goal of our research is to understand the fundamental physical and chemical factors that determine the efficiency and quality of pattern formation in Extreme Ultraviolet nanolithography. Various student projects ...

- **Ionic interactions in EUV-generating plasmas**
  - March 8, 2016 · [PhD positions](http://www.arcnl.nl)

  The group EUV plasma dynamics at ARCNL is looking for a PhD-student to work on 'Ionic interactions in EUV-generating plasmas'. The PhD project aims at unveiling and quantifying the fundamental ...